



HEAT ISLAND GROUP



Life-Cycle Assessment and Co-benefits of Cool Pavements

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thinkstep

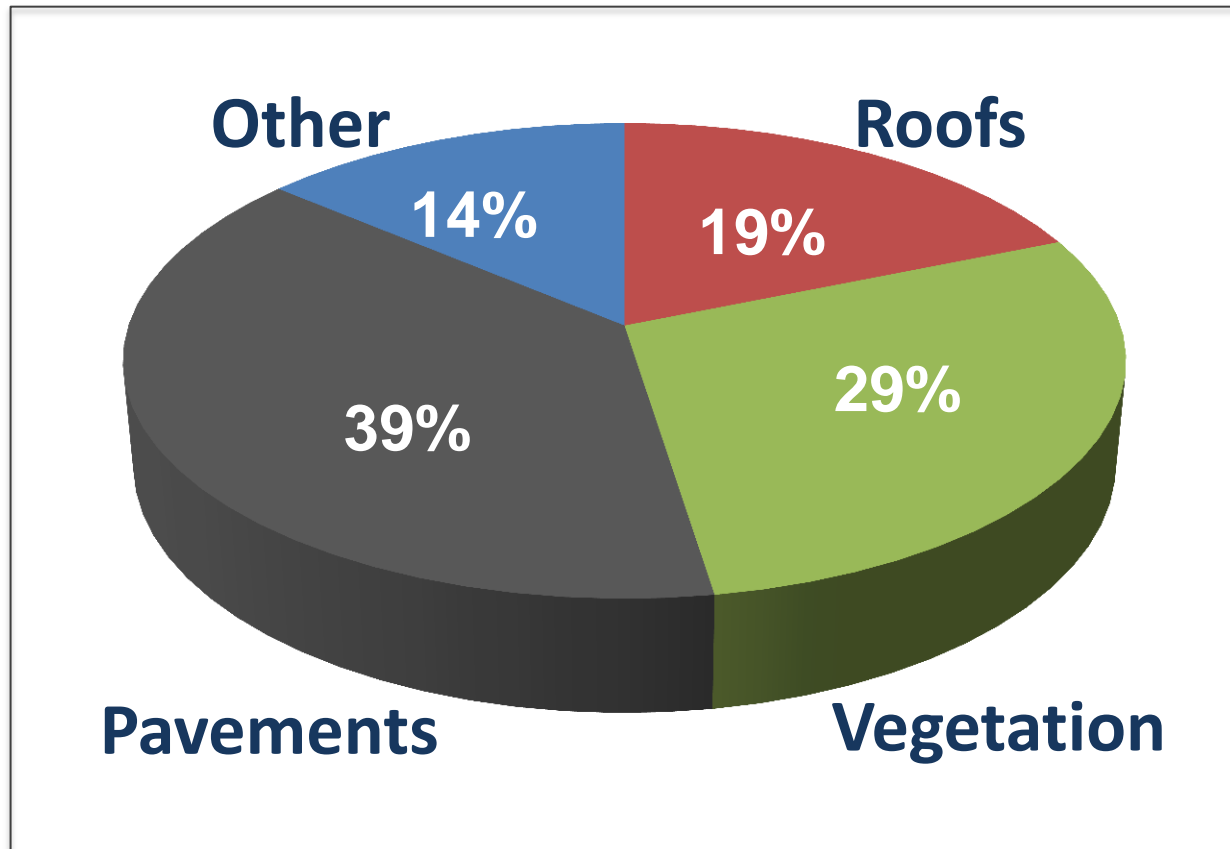
ARB Research Seminar

May 3, 2017

Sacramento, CA



Pavements are an important part of the urban environment



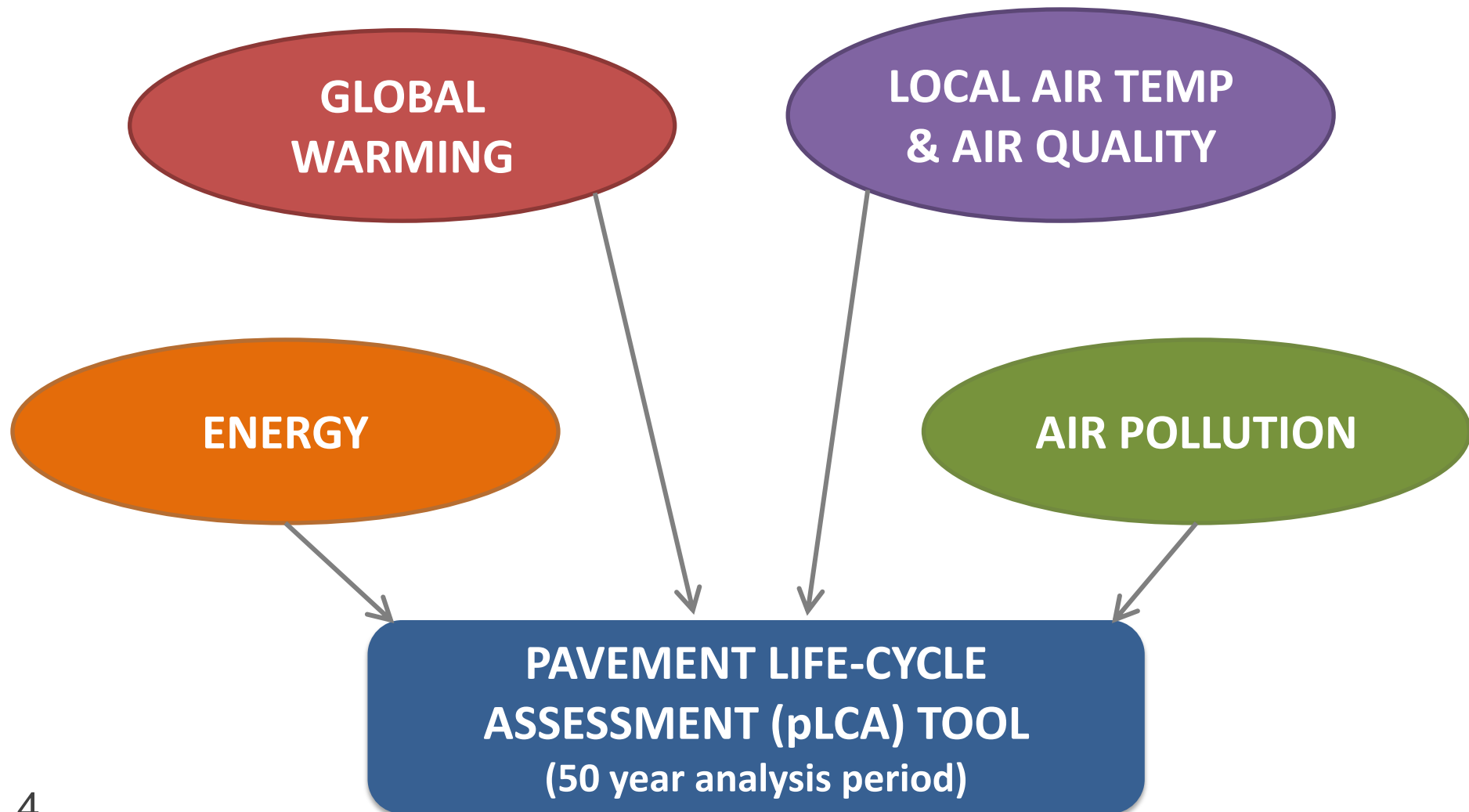
Sacramento

Fractions of land area were measured above tree canopy

Pavements can contribute to urban heat islands but can be designed to stay cooler



Project seeks to advise communities on energy and environmental consequences of "cool" pavements

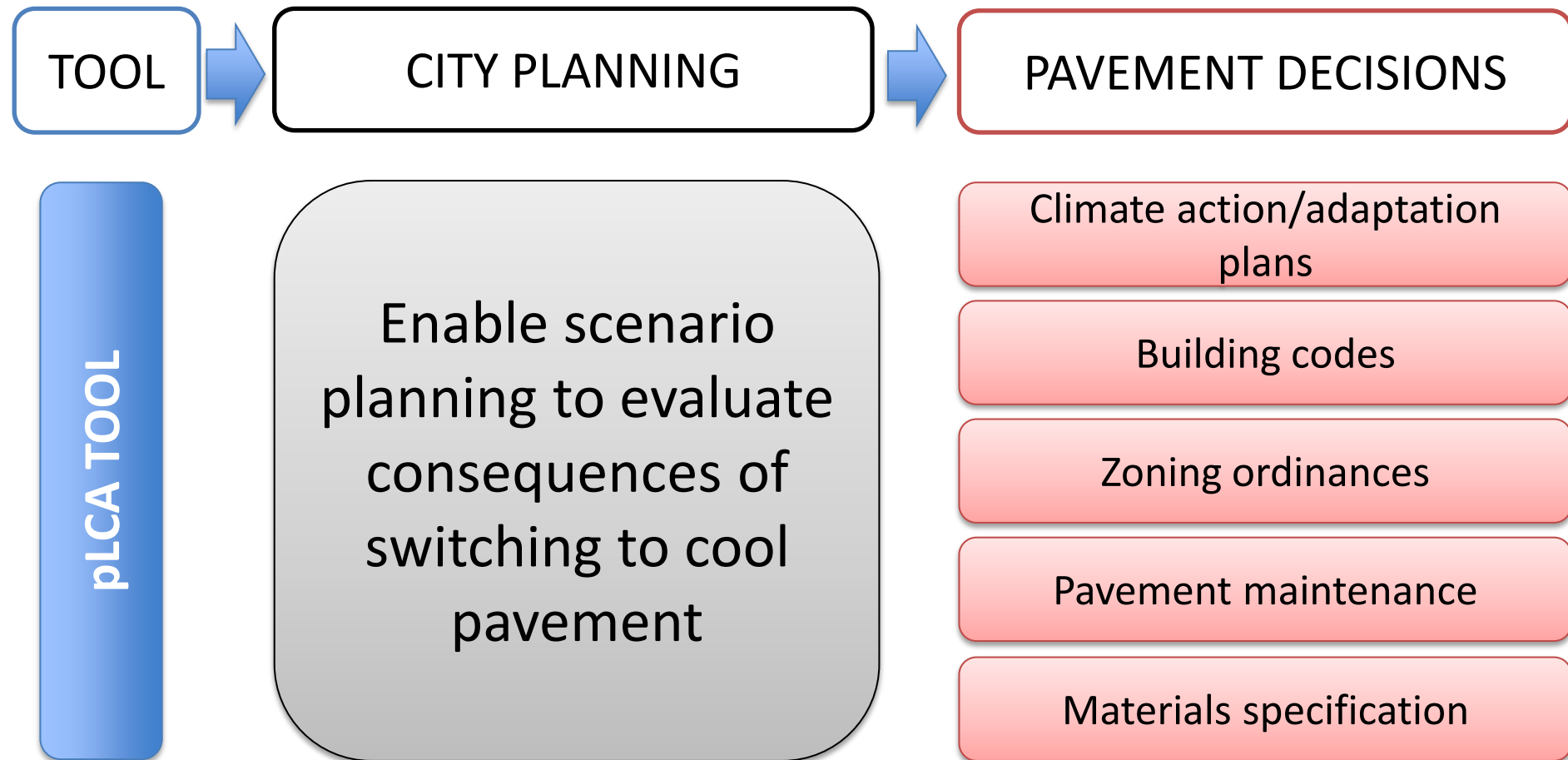


The pLCA tool can be useful in many contexts, but it was designed for local governments

- Study findings are relevant for a variety of pavements
 - E.g., those constructed and maintained by Caltrans
- However, local governments are the primary audience for the pLCA tool
 - Key project goals to facilitate decision-making at the local level, inform climate action planning, etc.



The tool presents life-cycle assessment (LCA) results to aid decision making



Pavement Life-Cycle Assessment Tool

Scope

Pavement manufacturing, construction, and transportation requires energy & produces emissions



Manufacture

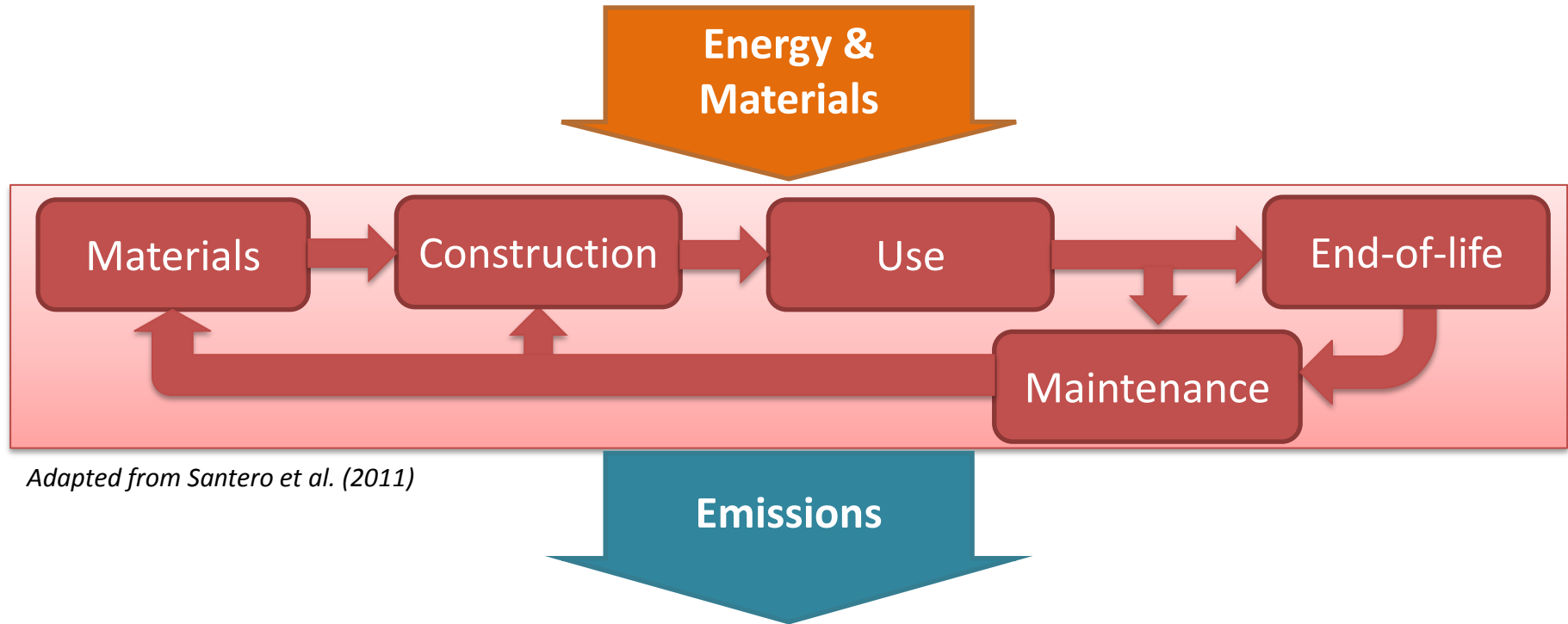


Construction



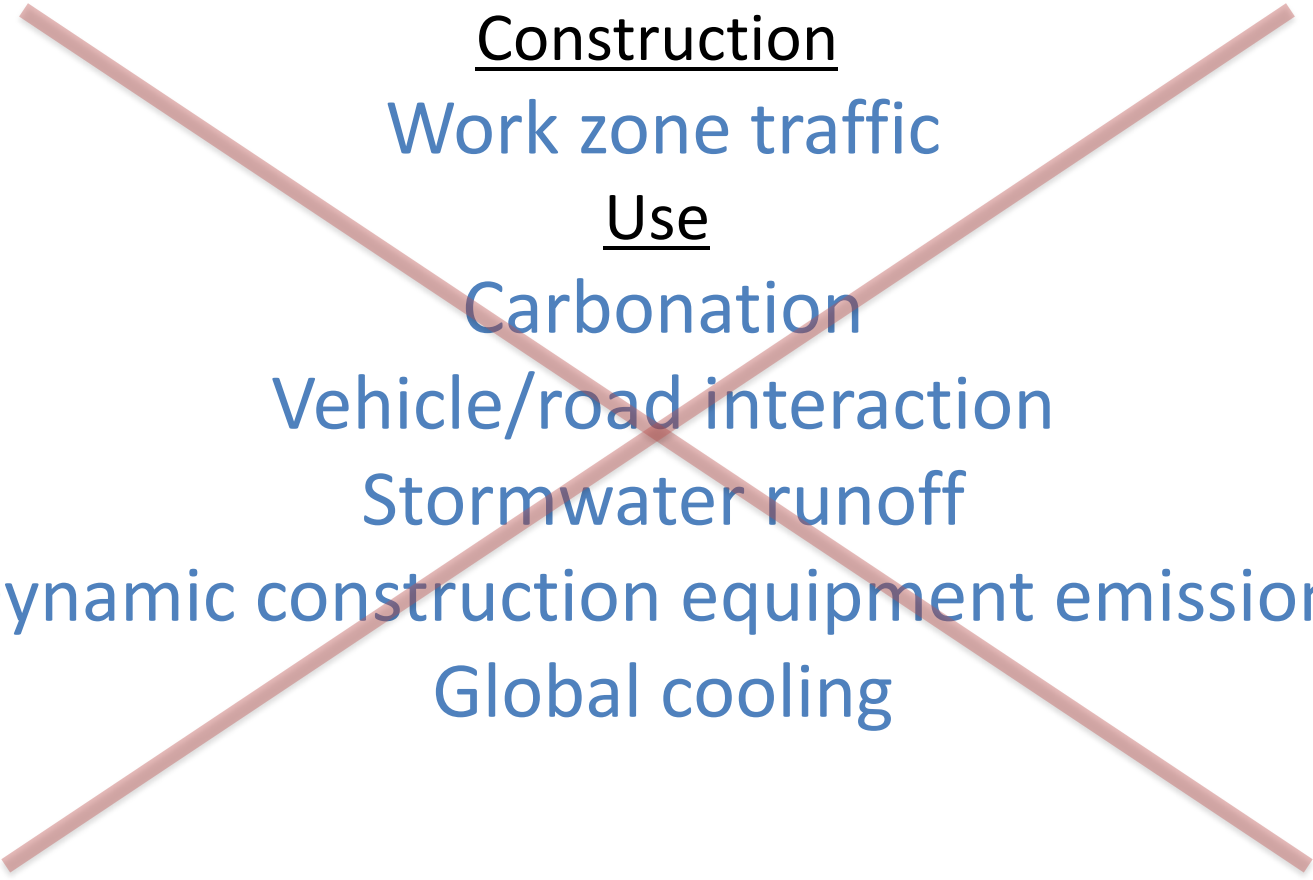
Transportation

We assessed energy and environmental effects across the 50-year pavement life-cycle stages



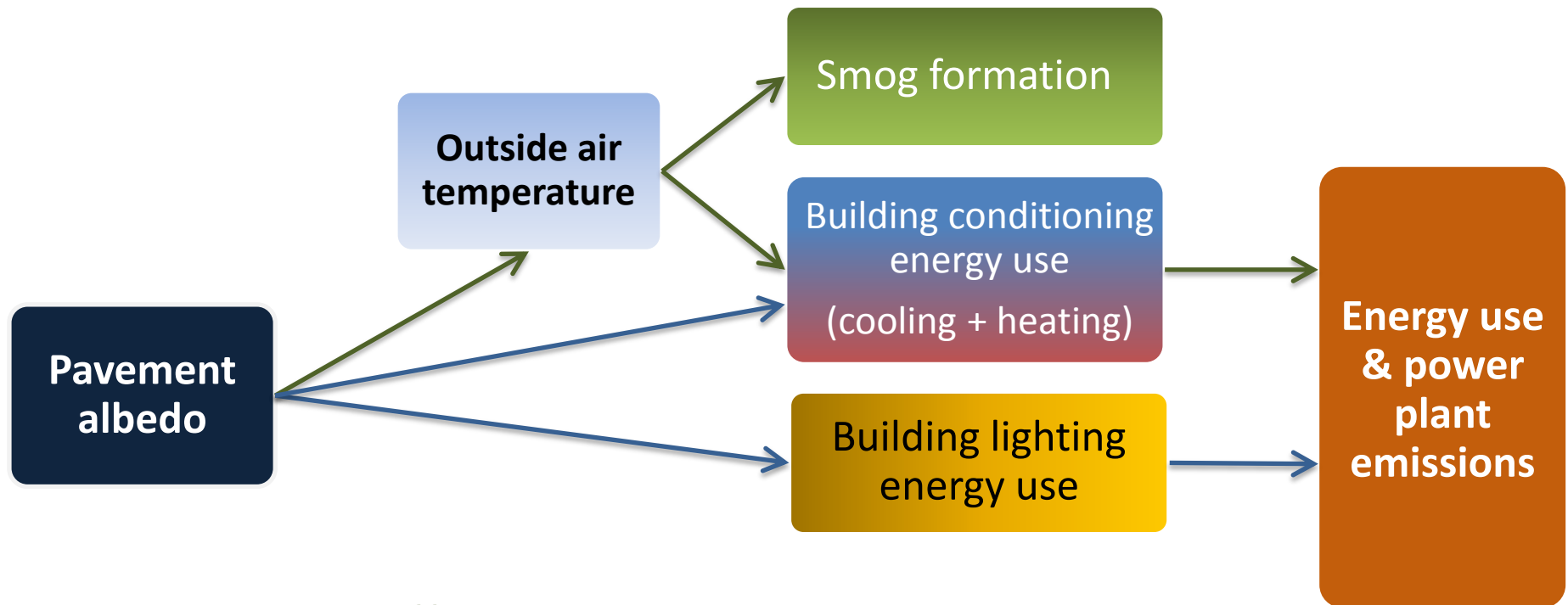
1. Materials and construction stage [MAC]
(materials, transportation, construction, end-of-life)
2. Use stage (cooling, heating, and lighting of buildings)

Many environmental impacts of the pavement life-cycle were beyond the scope of this project



Construction
Work zone traffic
Use
Carbonation
Vehicle/road interaction
Stormwater runoff
Dynamic construction equipment emissions
Global cooling

We analyzed use-stage effects that result from change in pavement albedo

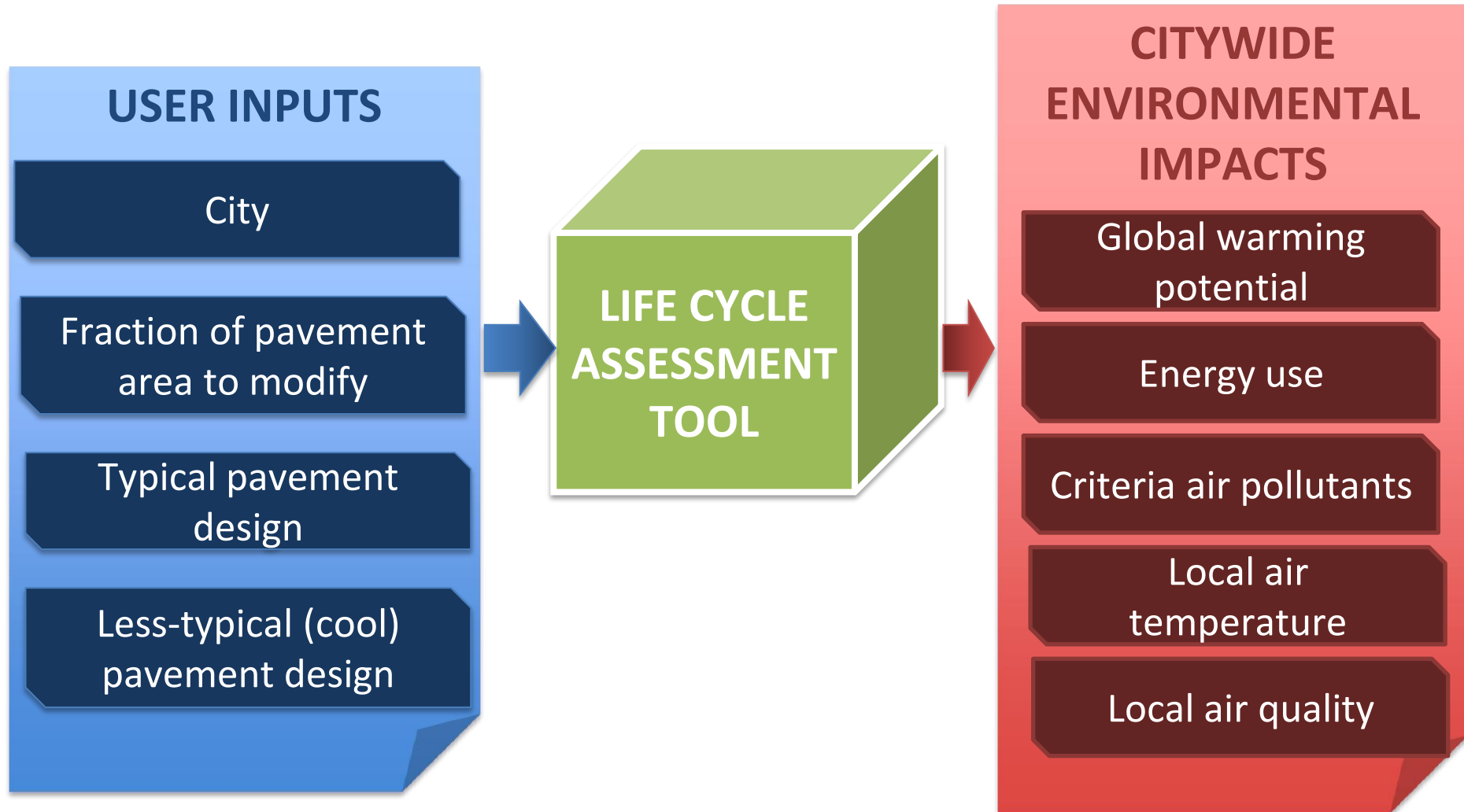


- Indirect effect
- Direct effect

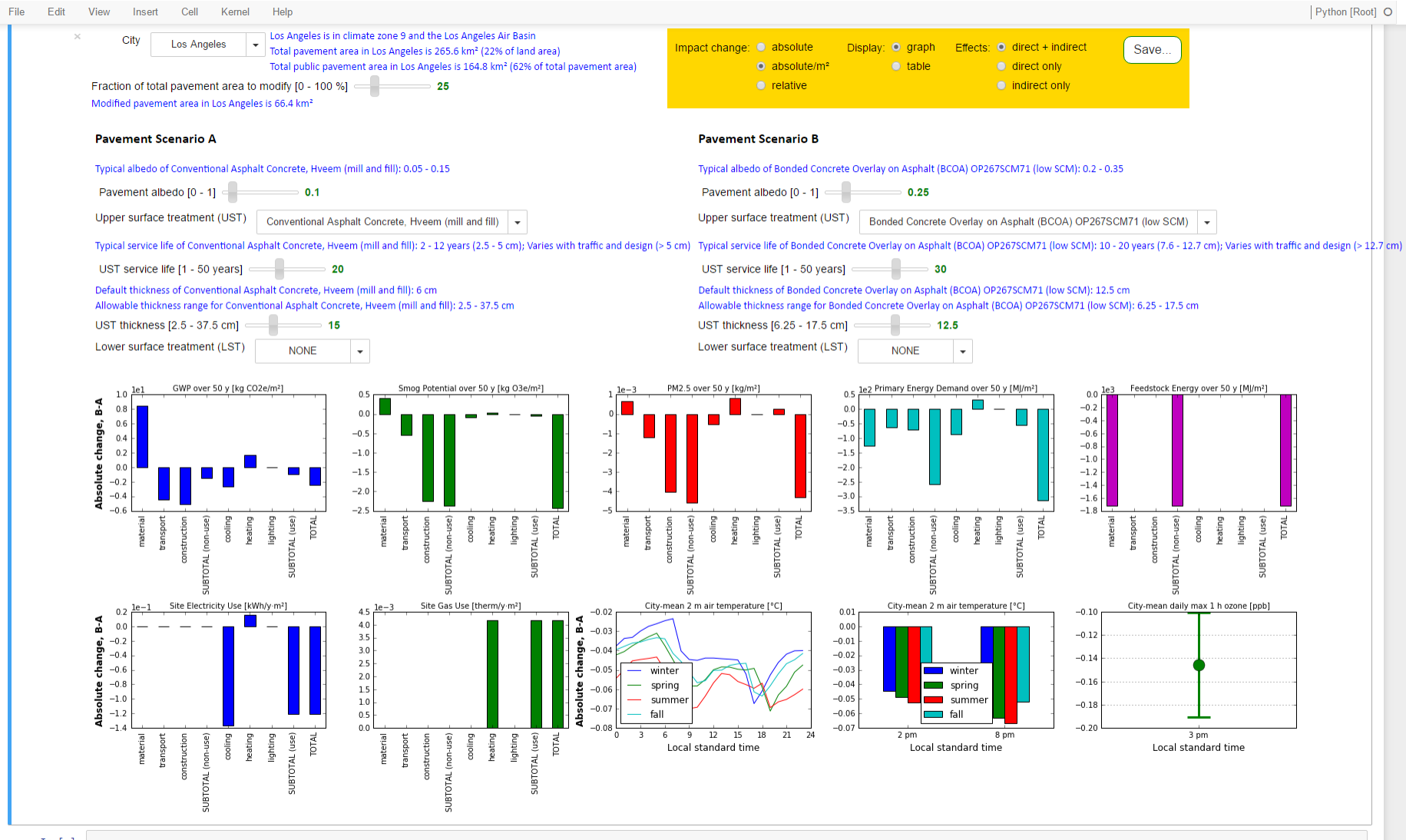
Pavement Life-Cycle Assessment Tool

Operating the Tool

To operate the tool, the user only needs to select a few inputs



The tool interface updates the results as the inputs change



The tool user selects inputs with drop-down menus and sliders

City

Los Angeles



Los Angeles is in climate zone 9 and the Los Angeles Air Basin

Total pavement area in Los Angeles is 265.6 km² (22% of land area)

Total public pavement area in Los Angeles is 164.8 km² (62% of total pavement area)

Fraction of total pavement area to modify [0 - 100 %]



25

Modified pavement area in Los Angeles is 66.4 km²

City & fraction
of modified
pavement
area

Pavement Scenario A



Typical pavement
design

Typical albedo of Conventional Asphalt Concrete, Hveem (mill and fill): 0.05 - 0.15

Pavement albedo [0 - 1]



0.1

Upper surface treatment (UST)

Conventional Asphalt Concrete, Hveem (mill and fill)



Typical service life of Conventional Asphalt Concrete, Hveem (mill and fill): 2 - 12 years (2.5 - 5 cm); Varies with traffic and des

UST service life [1 - 50 years]



20

Default thickness of Conventional Asphalt Concrete, Hveem (mill and fill): 6 cm

Allowable thickness range for Conventional Asphalt Concrete, Hveem (mill and fill): 2.5 - 37.5 cm

UST thickness [2.5 - 37.5 cm]



15

Lower surface treatment (LST)

NONE



Inputs and outputs can be viewed onscreen, or saved to CSV (tables) & PDF (graphs)

Impact change: ☐ absolute
☒ absolute/m²
☐ relative

Display: ☒ graph
☐ table

Effects: ☒ direct + indirect
☐ direct only
☐ indirect only

[Save...](#)

Controls for displaying results

Pavement Scenario B ← Less-typical “cool” pavement design

Typical albedo of Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 0.2 - 0.35

Pavement albedo [0 - 1] 0.25

Upper surface treatment (UST)

Typical service life of Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 10 - 20 years (7.6 - 12.7 cm);

UST service life [1 - 50 years] 30

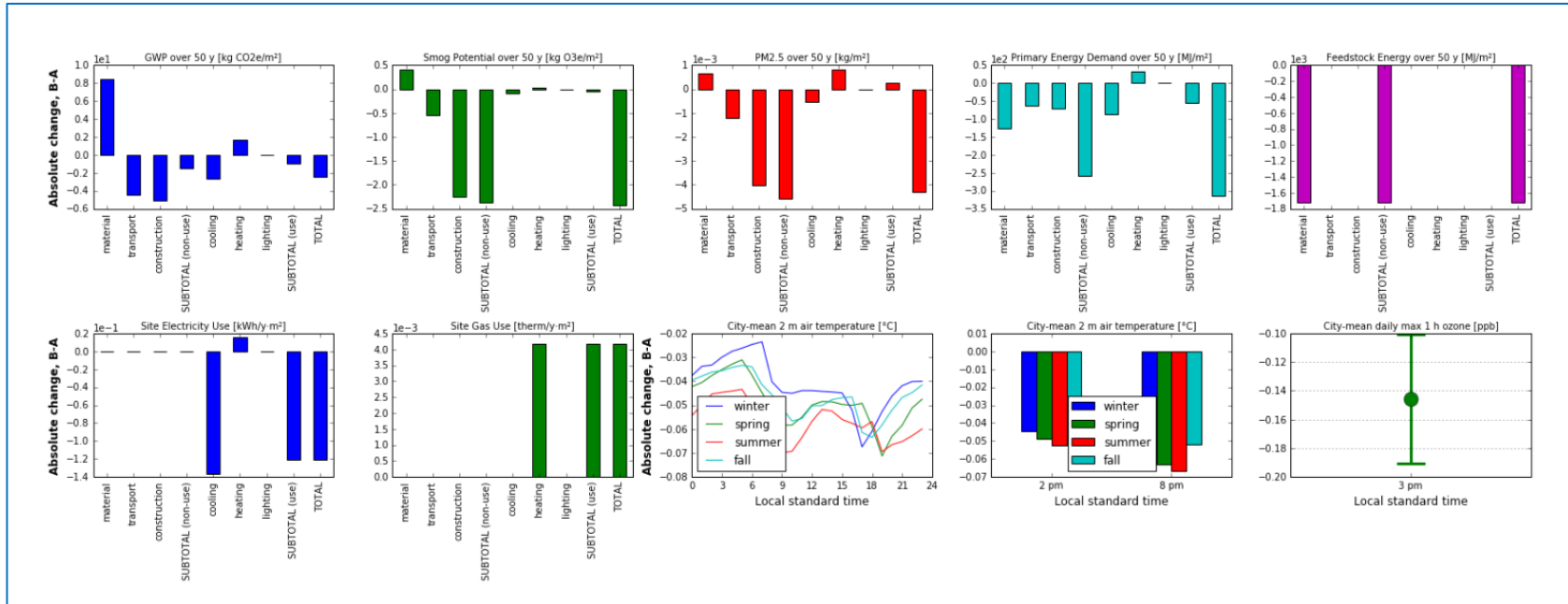
Default thickness of Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 12.5 cm

Allowable thickness range for Bonded Concrete Overlay on Asphalt (BCOA) OP267SCM71 (low SCM): 6.25 - 17.5 cm

UST thickness [6.25 - 17.5 cm] 12.5

Lower surface treatment (LST)

Outputs can be viewed as graphs or tables



Absolute impact change per unit area of pavement modified, B-A [direct + indirect]:

	GWP over 50 y [kg CO ₂ e/m ²]	Smog Potential over 50 y [kg O ₃ e/m ²]	PM _{2.5} over 50 y [kg/m ³]	Primary Energy Demand over 50 y [MJ/m ²]	Feedstock Energy over 50 y [MJ/m ²]	Site Electricity Use [kWh/y·m ²]	Site Gas Use [therm/y·m ²]
material	+8.43e+00	+4.09e-01	+6.72e-04	-1.26e+02	-1.73e+03	+0.00e+00	+0.00e+00
transport	-4.44e+00	-5.49e-01	-1.21e-03	-6.41e+01	+0.00e+00	+0.00e+00	+0.00e+00
construction	-5.11e+00	-2.25e+00	-4.01e-03	-7.03e+01	+0.00e+00	+0.00e+00	+0.00e+00
SUBTOTAL (non-use)	-1.54e+00	-2.38e+00	-4.57e-03	-2.60e+02	-1.73e+03	+0.00e+00	+0.00e+00
cooling	-2.63e+00	-8.69e-02	-5.49e-04	-8.59e+01	+0.00e+00	-1.37e-01	+0.00e+00
heating	+1.69e+00	+4.04e-02	+8.14e-04	+3.20e+01	+0.00e+00	+1.59e-02	+4.16e-03
lighting	-2.54e-04	-8.37e-06	-5.29e-08	-8.28e-03	+0.00e+00	-1.32e-05	+0.00e+00
SUBTOTAL (use)	-9.49e-01	-4.65e-02	+2.65e-04	-5.40e+01	+0.00e+00	-1.21e-01	+4.16e-03
TOTAL	-2.49e+00	-2.42e+00	-4.30e-03	-3.14e+02	-1.73e+03	-1.21e-01	+4.16e-03

Air temperature change, B-A [°C]:

	winter	spring	summer	fall
2 pm LST	-0.04	-0.05	-0.05	-0.05
8 pm LST	-0.05	-0.06	-0.07	-0.05

Ozone change at 3 pm LST [ppb]: -0.15 (range -0.19 to -0.10)

The tool reports LCA metrics, annual metrics, and instantaneous metrics

LCA metrics	Units
Global Warming Potential (GWP)	kg CO ₂ e*
Photochemical Ozone Creation Potential (POCP)**	kg O ₃ e
Particulate Matter, less than 2.5 micrometers in diameter (PM2.5)	kg
Primary Energy Demand (PED) excluding feedstock energy	MJ
Feedstock Energy (FE)	MJ
Use-stage metrics	Units
Annual Site Electricity Use	kWh/y
Annual Site Gas Use	therm/y
Outdoor Air Temperature (city mean, near the top of the urban canopy)	°C
Ozone Concentration (city mean at 15:00 local standard time)	parts per billion (ppb)

*CO₂e, or carbon dioxide equivalent, is a standard unit for measuring carbon footprints or “global warming potential.” The idea is to express the impact of each different greenhouse gas in terms of the amount of CO₂ that would create the same amount of warming.

**POCP (O₃e) is used to classify compounds according to their ability to form tropospheric ozone. Similar to the CO₂e unit for GWP, O₃e is used to express different emission compounds in terms of the amount of O₃ that would have the same impact on formation of smog.

Pavement Life-Cycle Assessment Tool

Methodology (for developing the tool)

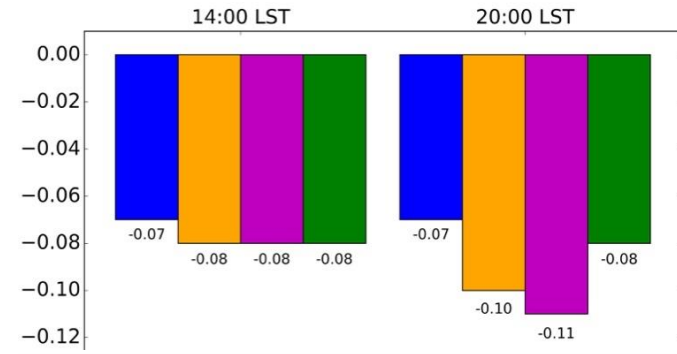
Tool applies datasets and algorithms developed through complementary research efforts



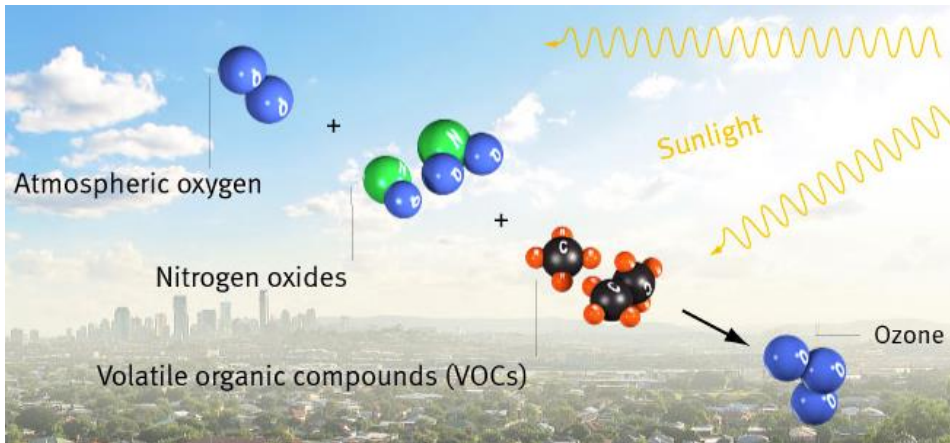
Local pavement practices



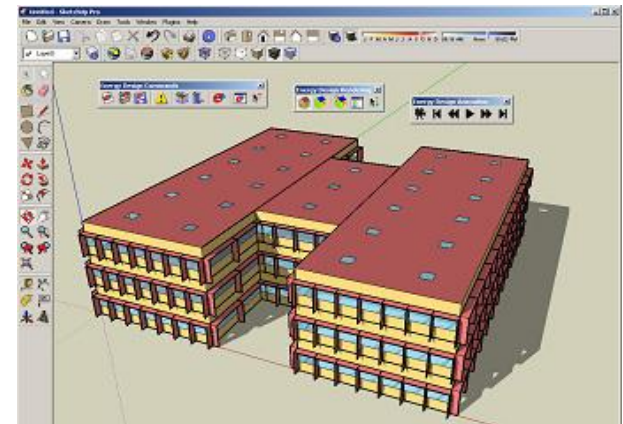
CA life-cycle inventories



Urban climate modeling



Urban air quality



Building energy modeling

We investigated pavement management and maintenance practices used by local governments in California

- Conducted interviews with 8 cities to survey their pavement practices
- Cities interviewed treated 1.3 to 20% of their pavement networks annually



Slurry seal
Used for 28 to 82%
of treated area
(average 41%)



Asphalt overlay
Used for 13 to 100%
of treated area
(average 37%)

We developed California-specific pavement material and electrical energy production life-cycle inventories



Based on CA utilities' projected electric grid mix in 2020 using Renewable Portfolio Standard



thinkstep
GaBi



Manufacture



Construction



Transportation

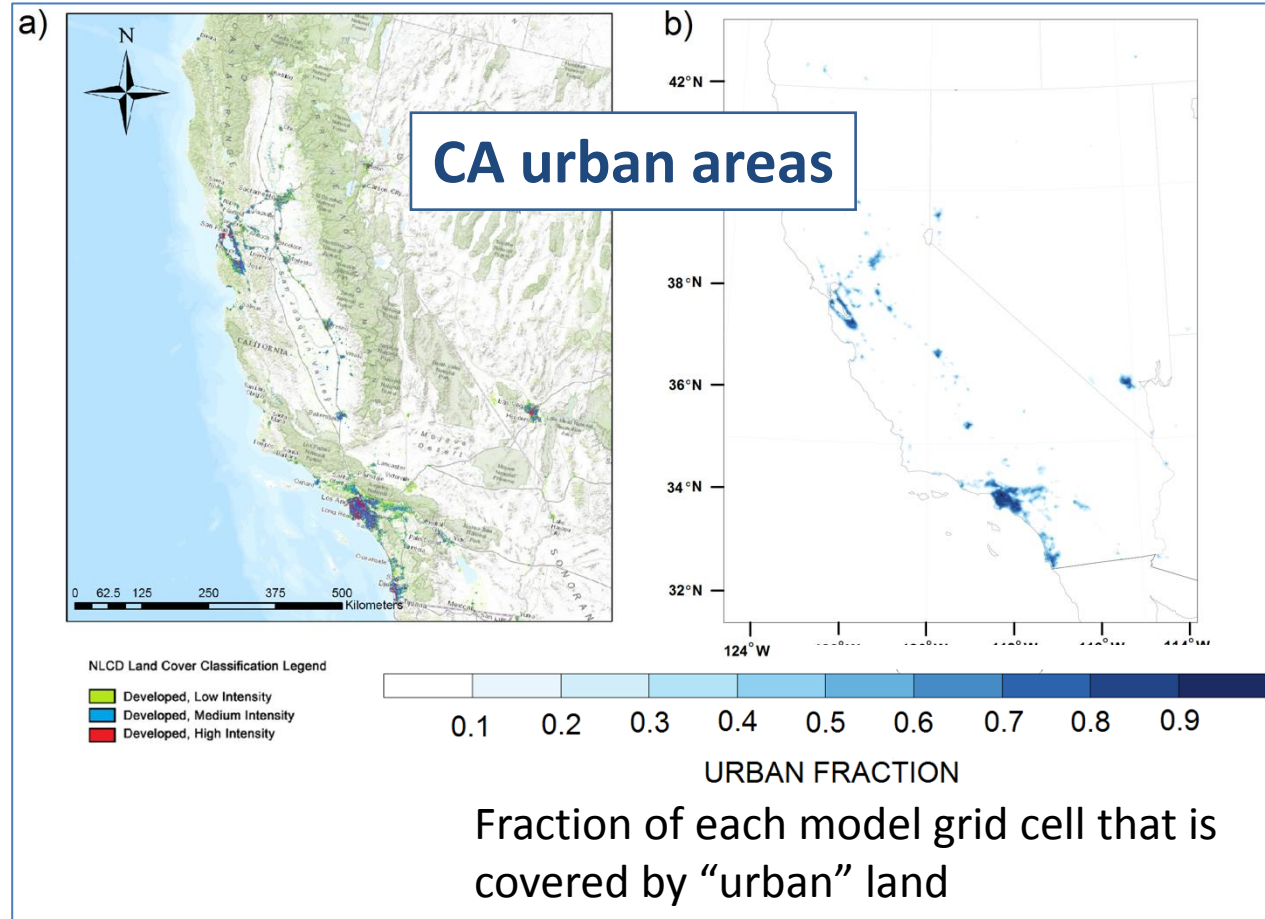
We modeled urban climate to estimate city-wide air temperature reductions from cool pavement adoption



Low albedo pavement



Higher albedo pavement



Moheggh et al. 2017

Simulated increases in pavement albedo in CA urban areas

We estimated reduction in urban ozone concentration when cool pavements lower air temperature

1. Reviewed literature for modeled and observed ozone-temperature sensitivities in CA air basins

CA Air Basins



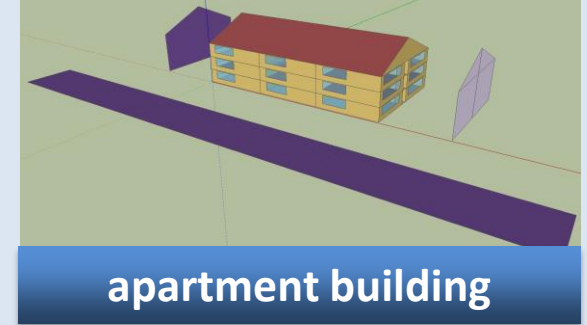
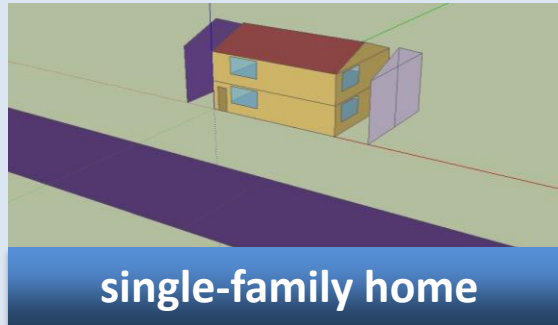
Air basins outlined in gold consistently exceed National Ambient Air Quality Standards for ground-level ozone.

2. Applied sensitivities to our modeled air temperature results at 14:00 local standard time to calculate urban ozone changes

We modeled buildings to calculate changes in energy use from modifying albedo of city and local streets

Residential

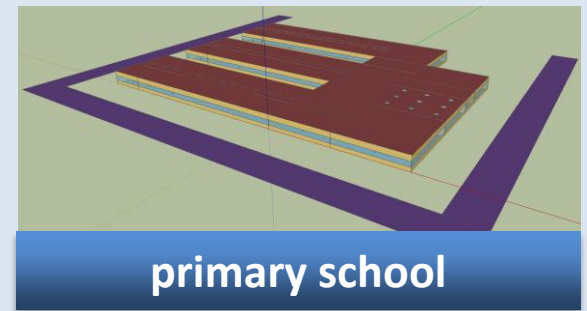
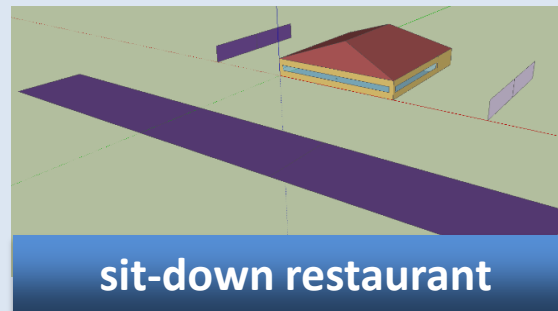
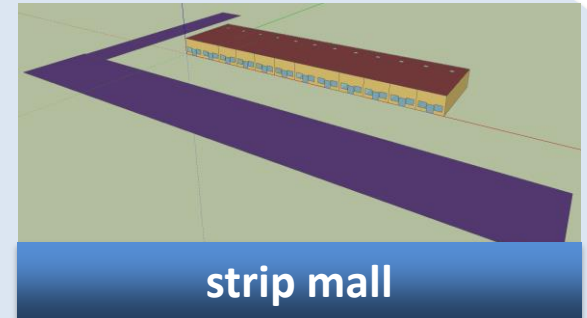
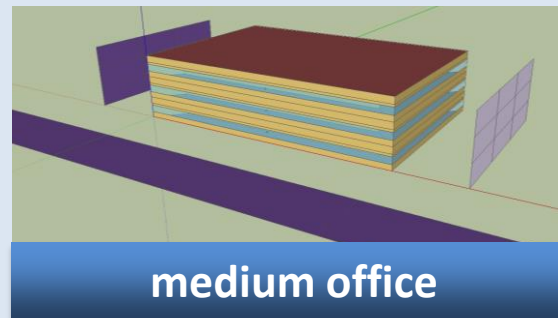
- single-family home
- apartment building



**10 prototypes
were modeled**

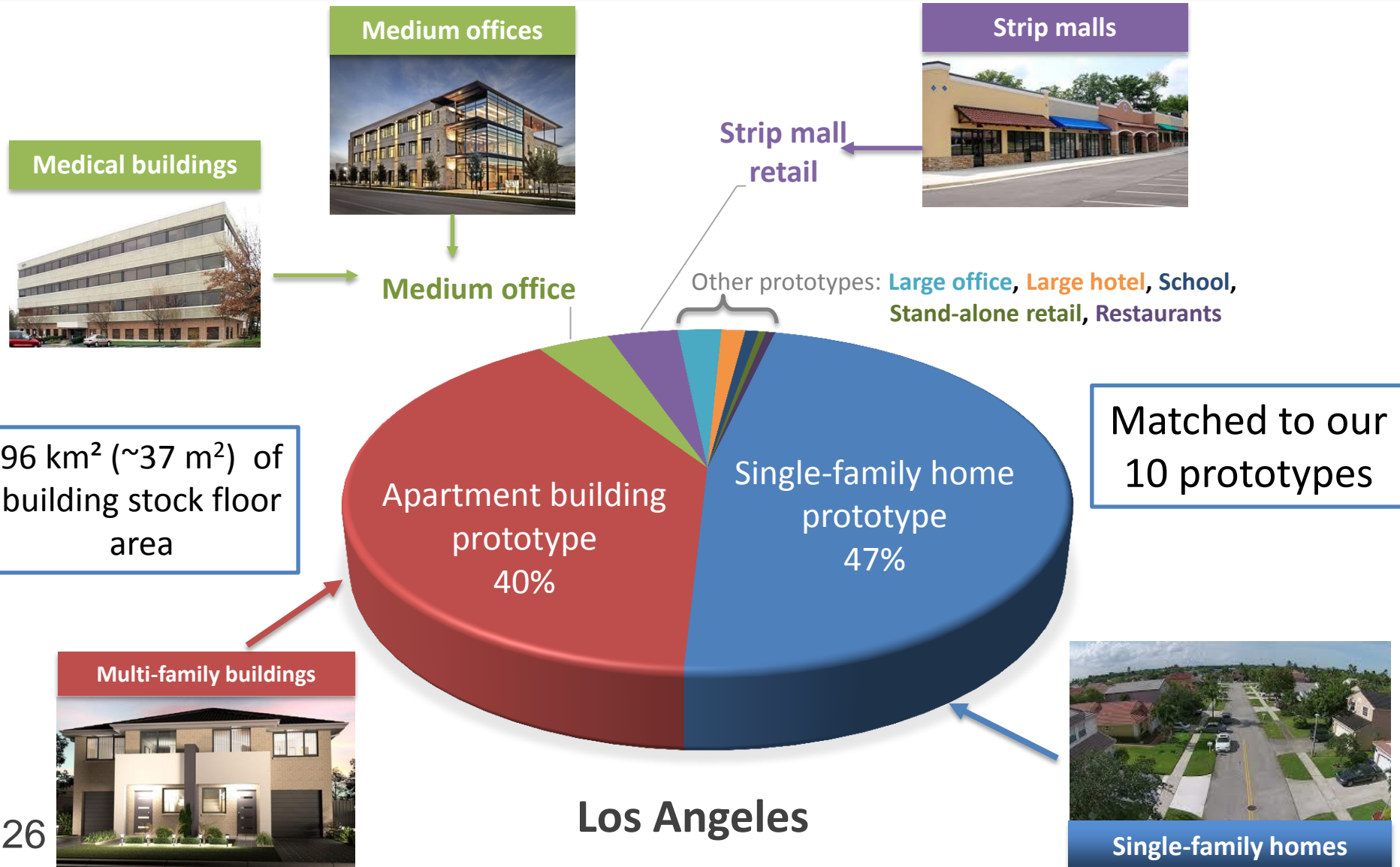
Commercial

- 2 offices
- 2 retail
- 2 restaurants
- primary school
- large hotel



EnergyPlus v. 8.5

We matched each city's building stock to the 10 prototypes to calculate city-wide changes



Pavement Life-Cycle Assessment Tool

Case Studies

Gilbert HE, Rosado PJ, Ban-Weiss G, Harvey JT, Li H, Mandel BH, Millstein D, Mohegh A, Saboori A, Levinson RM. 2017. Energy and environmental consequences of a cool pavement campaign. *Energy and Buildings*, in press.

<http://doi.org/10.1016/j.enbuild.2017.03.051>

We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (i)



Routine maintenance case study

Treatment	Case study
Slurry seal	Typical pavement for Case 1A
Styrene acrylate reflective coating	Less-typical pavement for Case 1A

We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (ii)

Mill-and-fill asphalt concrete (AC)



Bonded concrete overlay on asphalt (BCOA)



Rehabilitation case study

Treatment	Case study
Mill-and-fill AC	Typical pavement for Cases 2A, 2B, and 2C
BCOA (no SCM)	Less-typical pavement for Case 2A
BCOA (low SCM)	Less-typical pavement for Case 2B
BCOA (high SCM)	Less-typical pavement for Case 2C

SCM = supplementary cementitious materials

Case study	Typical treatment	Less-typical treatment	Aged albedo	Albedo increase	Service life (y)	Thickness per installation (cm)	Thickness installed over 50 y (cm)
1. Routine maintenance	Slurry seal		0.10	-	7	-	-
		1A: Styrene acrylate reflective coating	0.30	0.20	5	-	-
2. Rehabilitation	Mill-and-fill AC		0.10	-	10	6	30
		2A: BCOA (no SCM)	0.25	0.15	20	10	25
		2B: BCOA (low SCM)	0.25	0.15	20	10	25
		2C: BCOA (high SCM)	0.25	0.15	20	10	25

***Case study 3 is similar but with longer lives and thicker pavements**

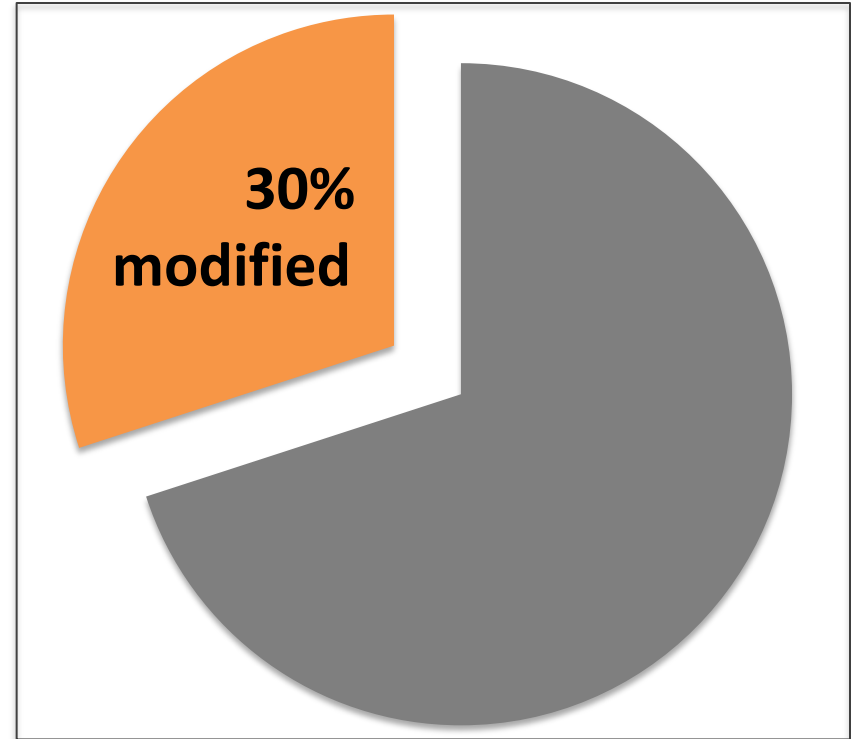
METRICS

**Global Warming Potential
(GWP), kg of CO₂e**

**Primary Energy Demand
(PED) w/o FE, MJ**

**Outdoor Air
Temperature, °C**

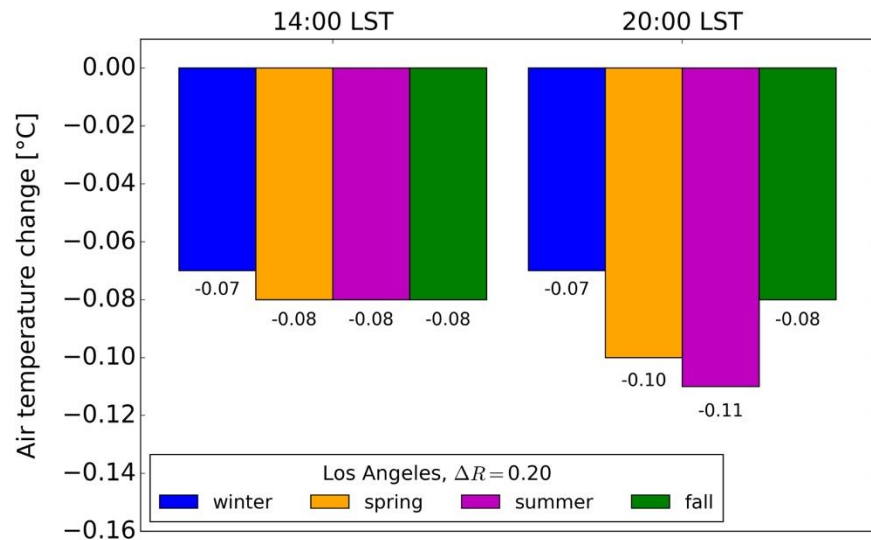
All cases evaluated for Fresno and Los Angeles with 30% of city pavement modified



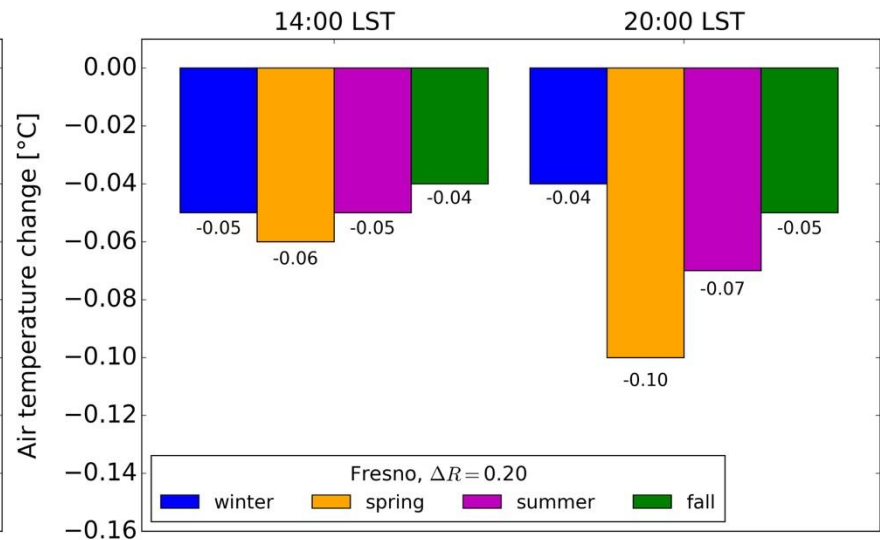
city pavement

The modeled changes to air temperature are consistent with other urban heat island mitigation strategy studies

Simulated cooling rate (0.9°C per 0.1 increase in urban albedo) matches Santamouris (2014)

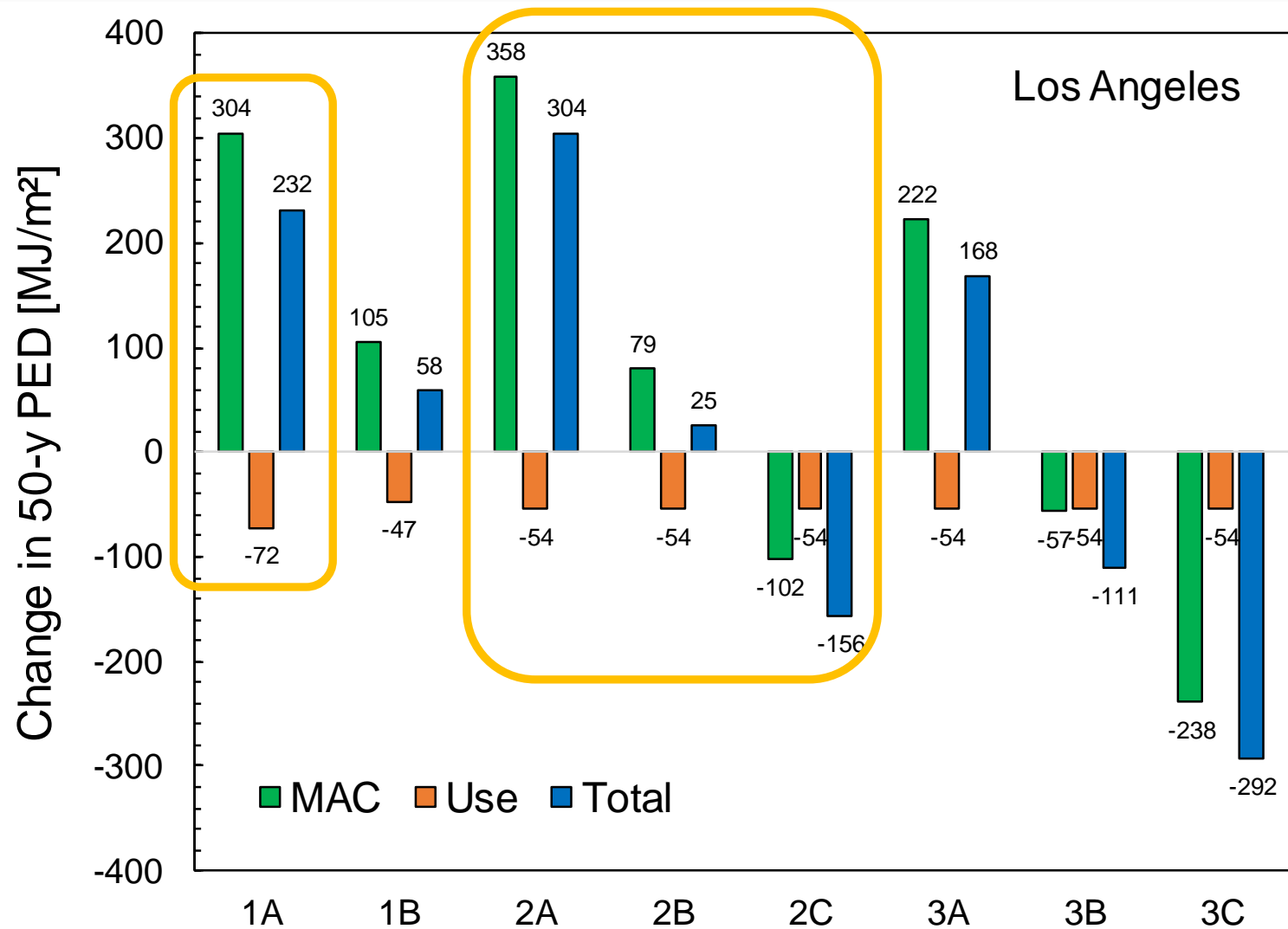


Los Angeles

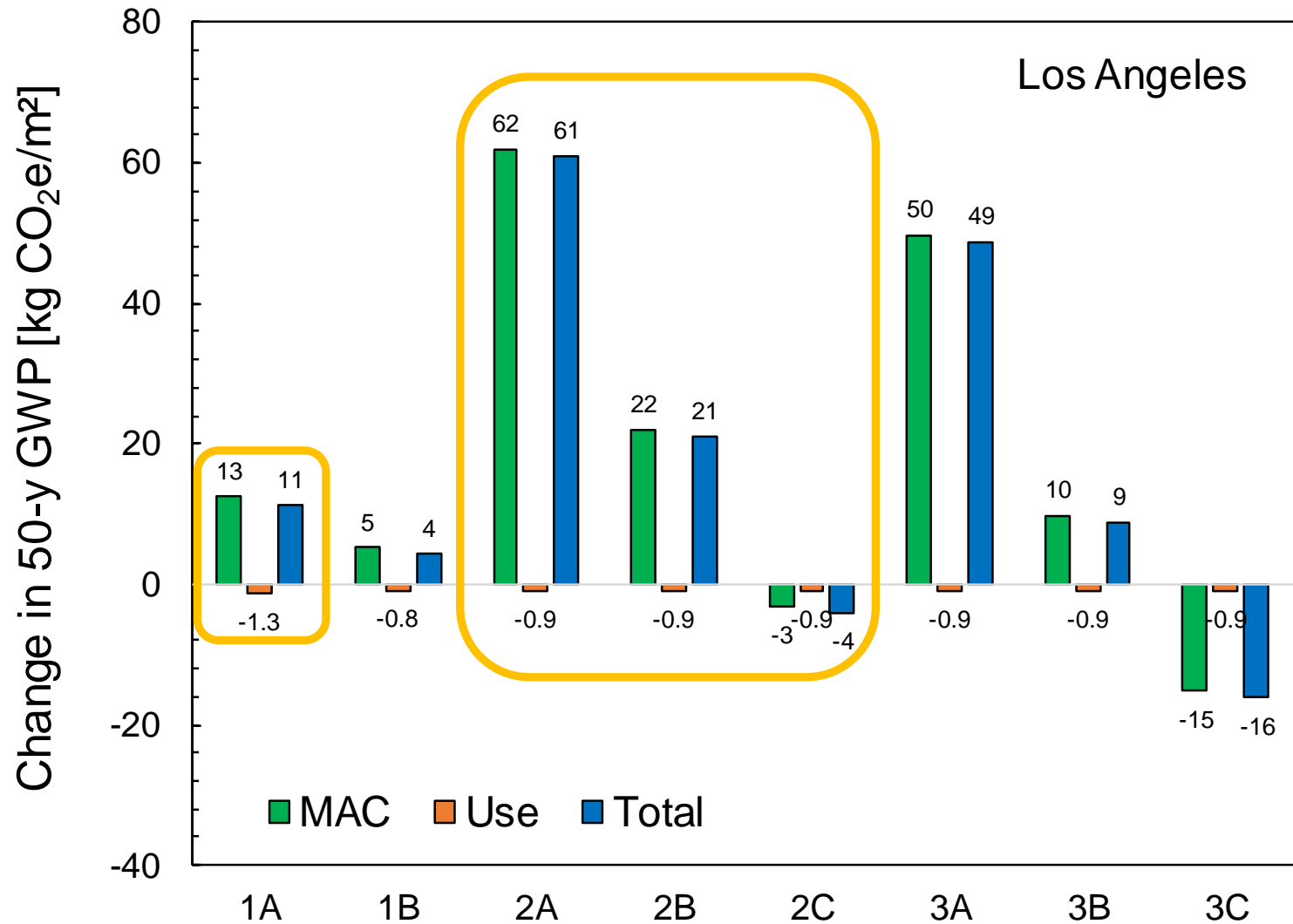


Fresno

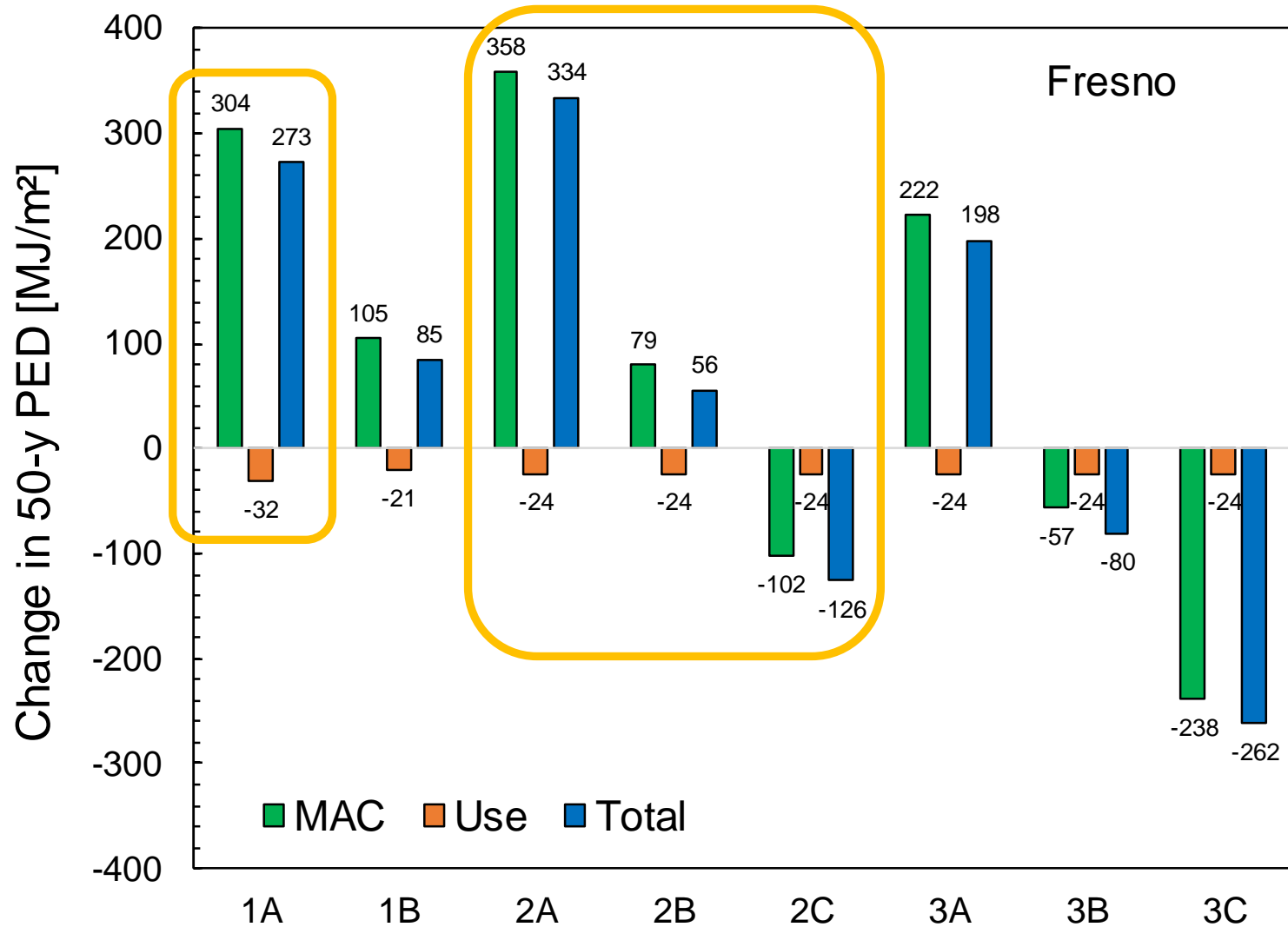
The materials & construction (MAC) stage primary energy demand (PED) changes exceed use-stage changes in LA



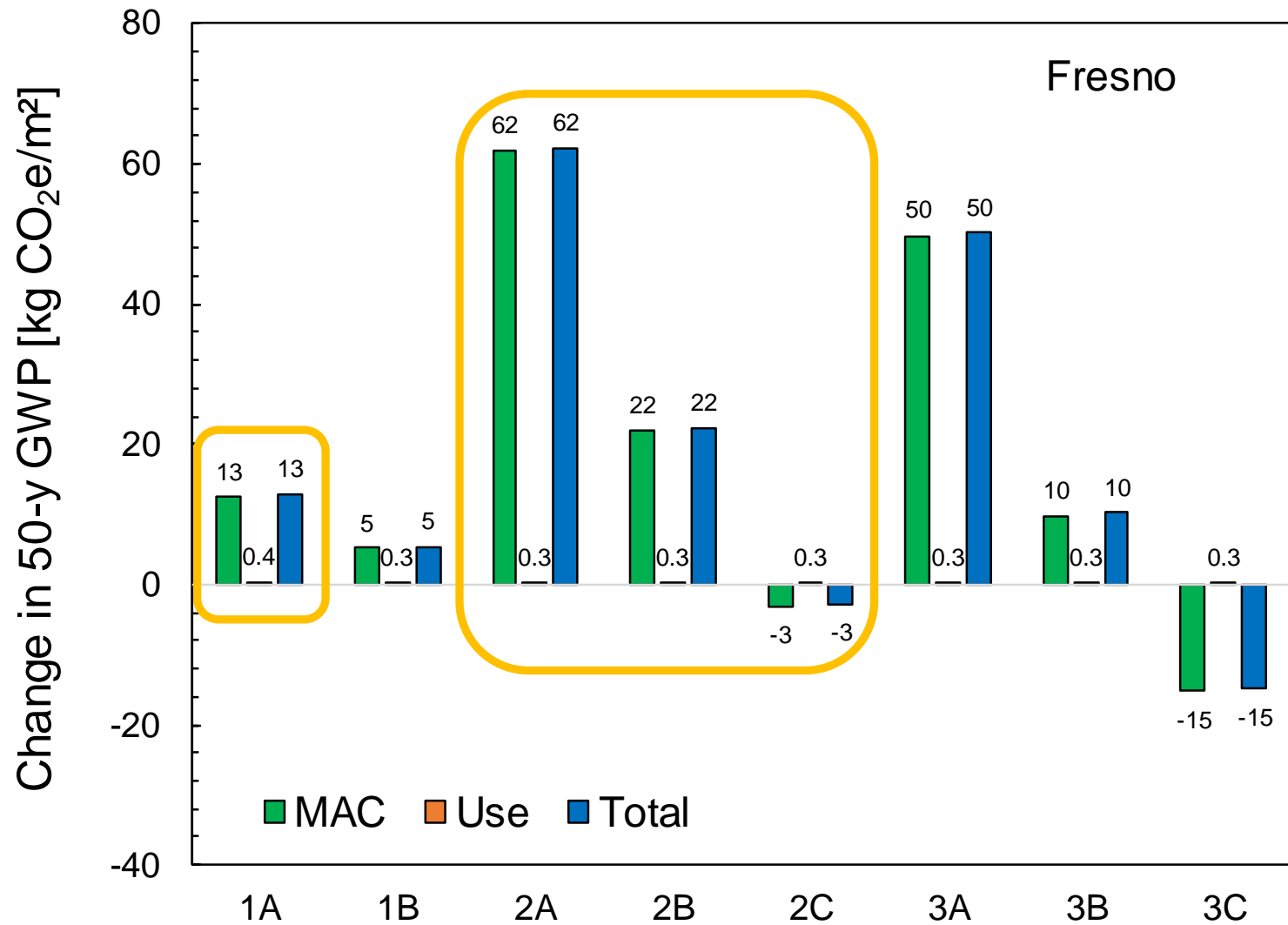
The MAC-stage global warming potential changes exceed use-stage changes in LA



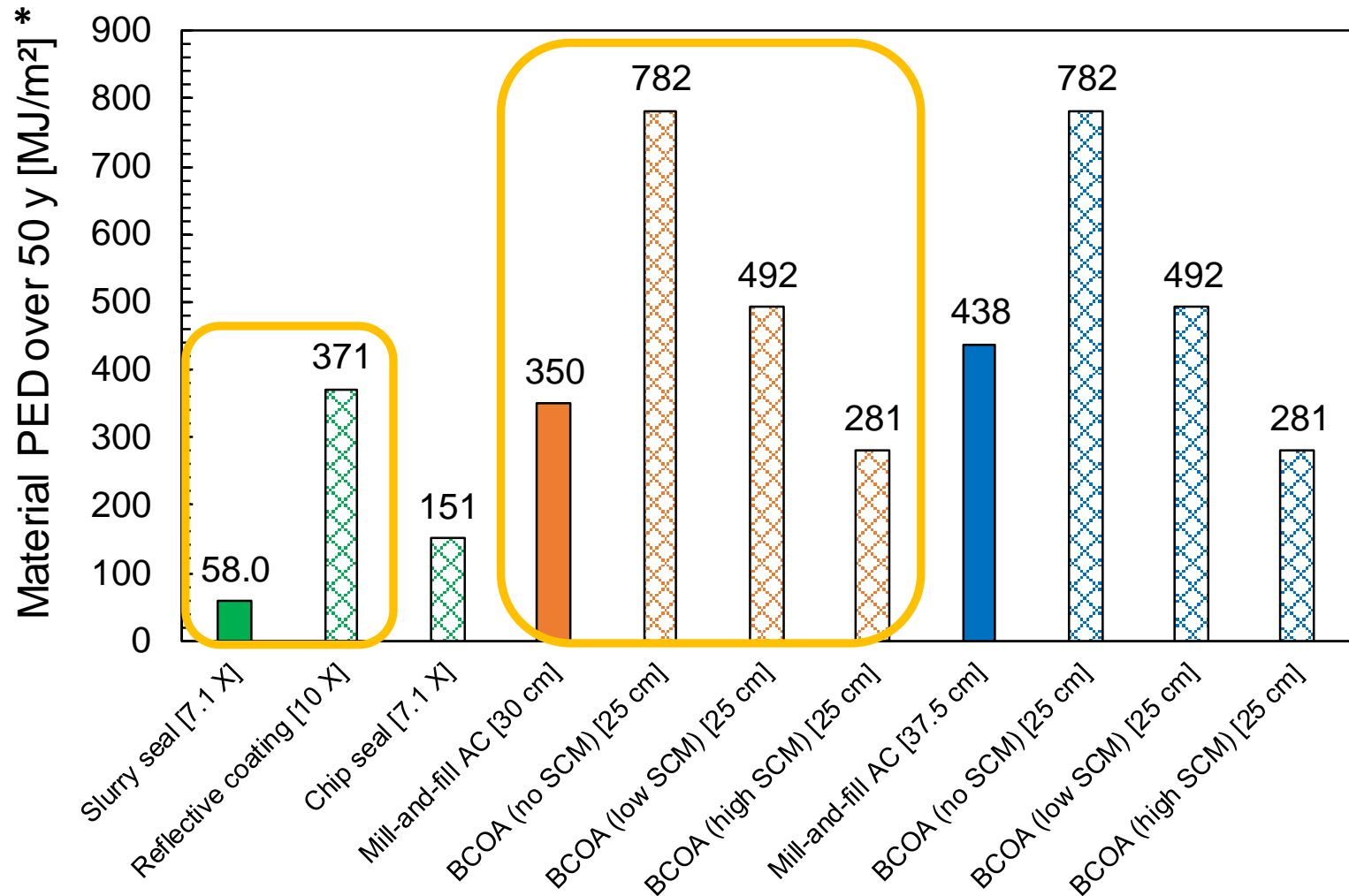
The MAC-stage primary energy demand changes exceed use-stage changes in Fresno



The MAC-stage GWP changes exceed use-stage changes in Fresno

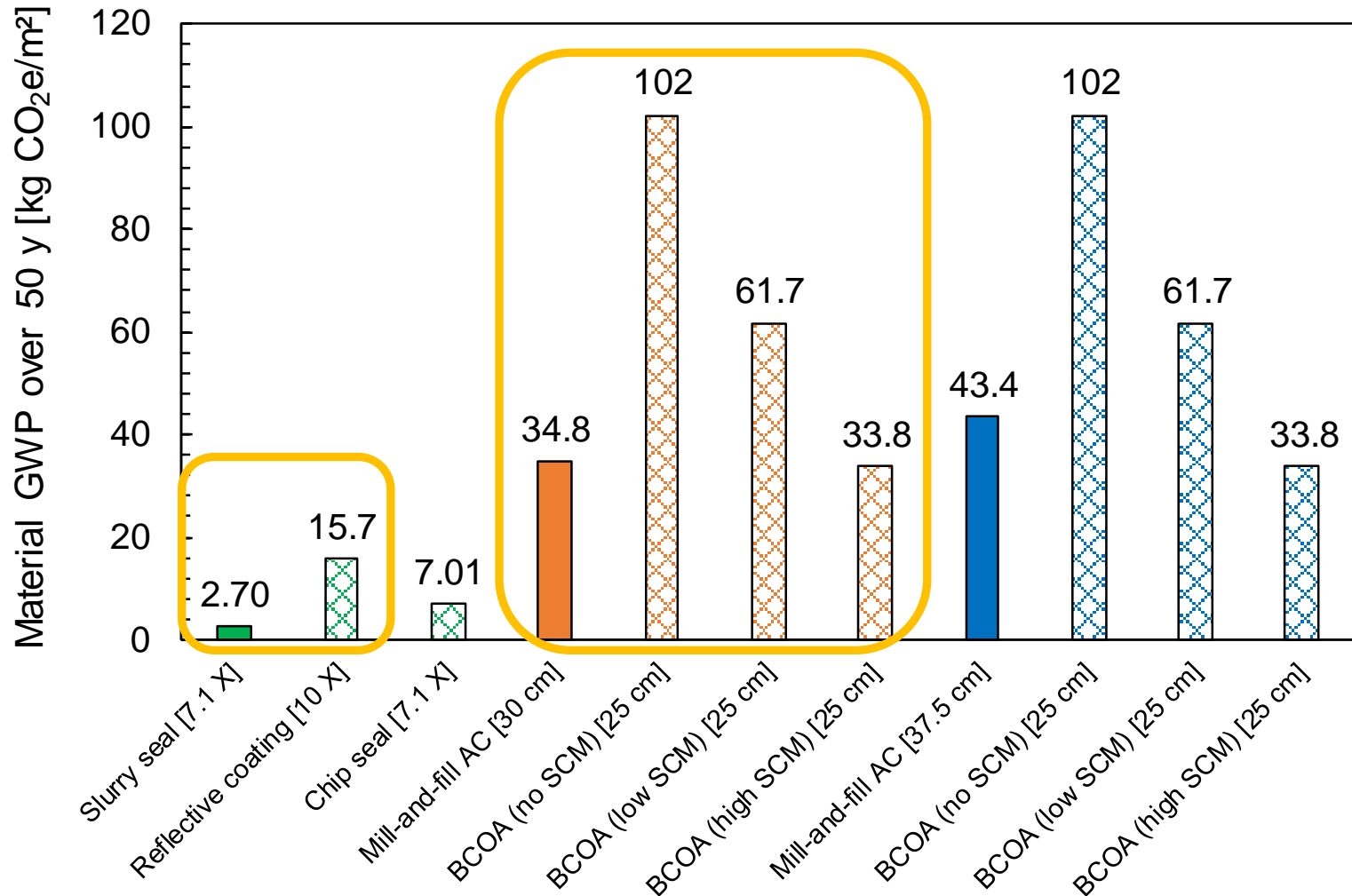


The manufacture of cool pavements is frequently more energy intensive than typical treatments



* Feedstock energy reported separately

It also tends to be more carbon intensive



The results can be evaluated in the context of city GHG emission goals

Los Angeles

Case Study	Increase in annual GWP (Mt CO ₂ e)			
	Reflective coating [1A]	BCOA (no SCM) [2A]	BCOA (low SCM) [2B]	BCOA (high SCM) [2C]
1. Routine maintenance	0.018			
2. Rehabilitation		0.097	0.034	-0.006

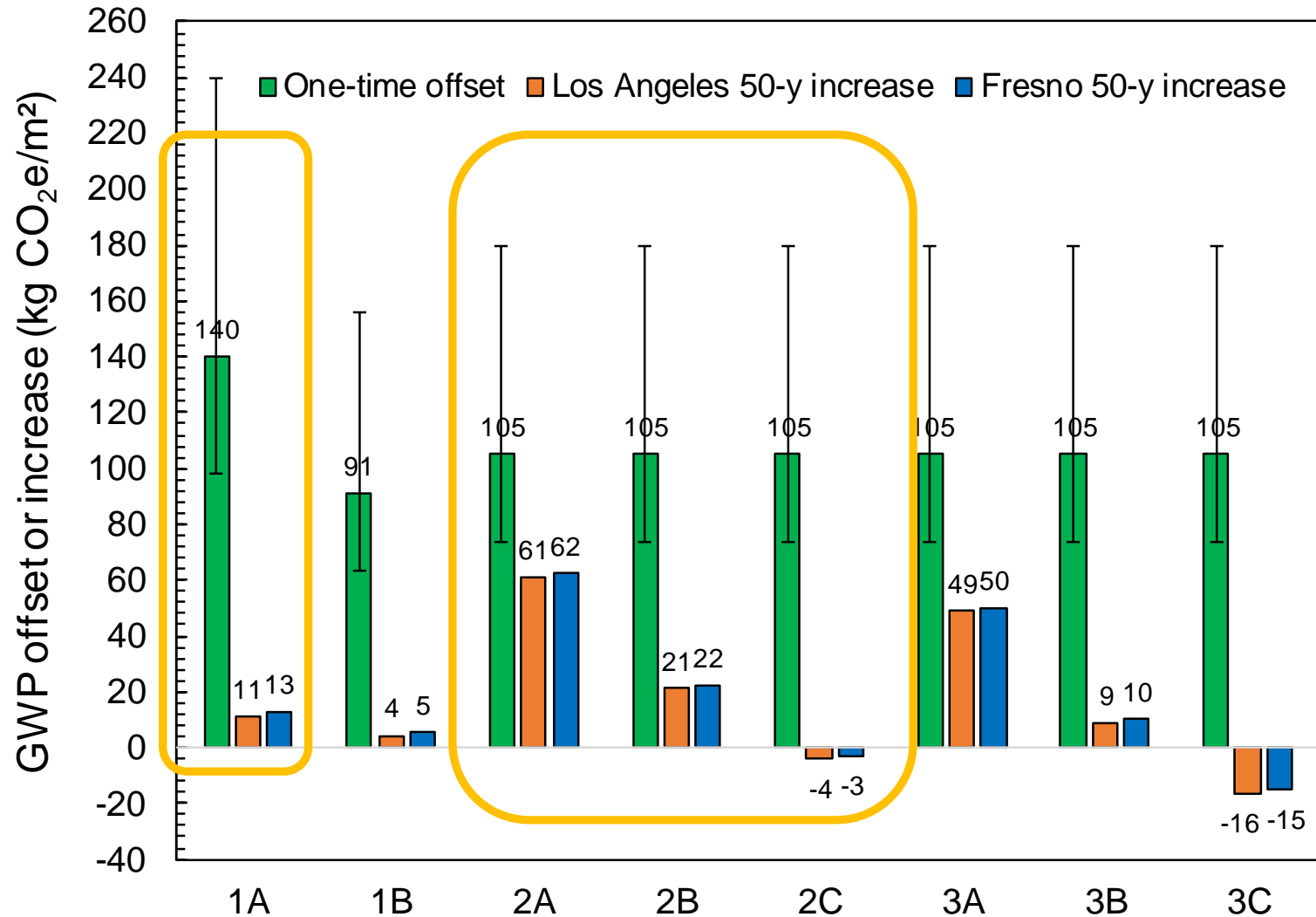
Los Angeles has a 2025 GHG emission target:

20 Mt/y CO₂e

Relative to this target, the city-wide GWP change ranges

from savings 0.03% to penalty 0.49%

The *one-time* GWP offset from global cooling exceeds the changes in 50-y life-cycle GWP



IPCC AR5; Akbari et al. 2012
<doi:10.1088/1748-9326/7/2/024004>

Annual building energy cost savings for cool pavements are less than those for cool roofs

Substituting a reflective coating for a slurry seal (albedo increase 0.20):

Building conditioning energy cost savings per square meter of pavement modified in LA

\$0.03/y



Substituting a cool roof for a dark roof (albedo increase 0.35):

Building conditioning energy cost savings per square meter of roof modified in LA

\$0.47/y



→ **15 times** the annual cool *pavement* conditioning energy cost savings

Pavement Life-Cycle Assessment Tool

Conclusions

Key takeaways about cool pavements: 50-year life-cycle changes in PED, GWP

For case studies:

- In use stage,
 - PED decreases in LA and Fresno
 - GWP decreases in LA, increases in Fresno
- In MAC stage, PED and GWP usually rise
- MAC-stage changes typically \gg use-stage changes
- **Total PED, GWP tend to rise**

Key takeaways about cool pavements: mitigating life-cycle penalties

- 50-y GWP change $<$ or \ll than *one-time* global cooling GWP offset
- Introduction of new approaches for cool pavement materials (e.g., reducing cement content) can mitigate these impacts
- If cool pavements reduce global warming, and they are found to be cost effective relative to other strategies, then further work is warranted in the development of these technologies

Resources (i)

- CARB project website & link to final report
https://www.arb.ca.gov/research/single-project.php?row_id=65149
 - Information for accessing and operating the pLCA tool can be found in final report
(Section 2.8, beginning on page 57)
- Gilbert HE, Rosado PJ, Ban-Weiss G, Harvey JT, Li H, Mandel BH, Millstein D, Mohegh A, Saboori A, Levinson RM. 2017. Energy and environmental consequences of a cool pavement campaign. *Energy and Buildings*, in press.
<http://doi.org/10.1016/j.enbuild.2017.03.051>

Resources (ii)

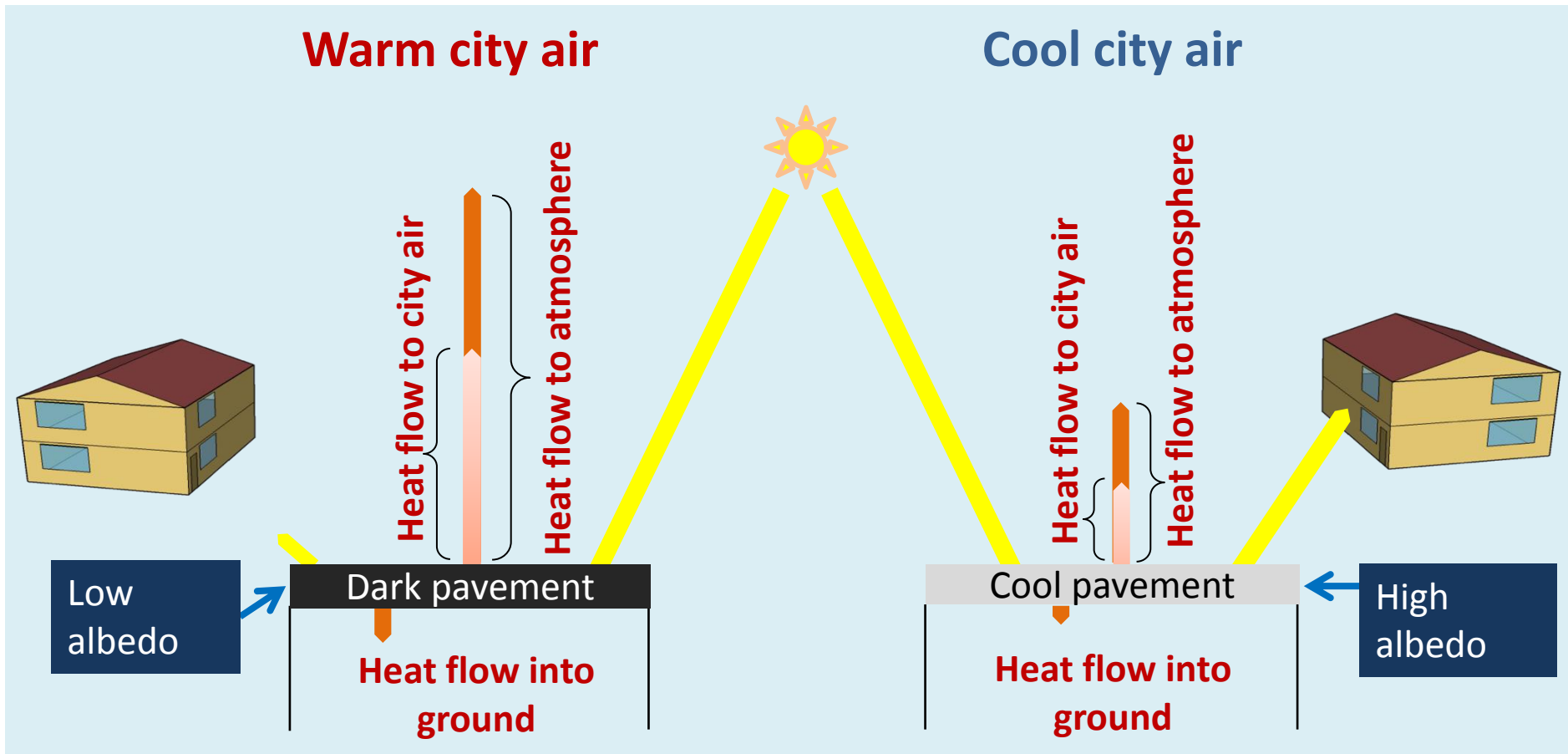
- Related publications

- Pomerantz M et al. 2015. A simple tool for estimating city-wide annual electrical energy savings from cooler surfaces. *Urban Climate* 14(2), 315-325. <https://doi.org/10.1016/j.uclim.2015.05.007>
- Pomerantz M. 2017. Are cooler surfaces a cost-effective mitigation of urban heat islands? *Urban Climate*, in press. <http://doi.org/10.1016/j.uclim.2017.04.009>
- Rosado P et al. 2017. Influence of street setbacks on solar reflection and air cooling by reflective streets in urban canyons. *Solar Energy* 144, 144-157. <https://doi.org/10.1016/j.solener.2016.12.026>
- Mohegh A et al. 2017. Modeling the climate impacts of deploying solar reflective cool pavements in California cities. *Journal of Geophysical Research*, in press.

Thank you!

Reference Slides

Pavements with high albedo can cool the city air, but may increase reflected sunlight that strikes buildings



We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (i)



Routine maintenance case study

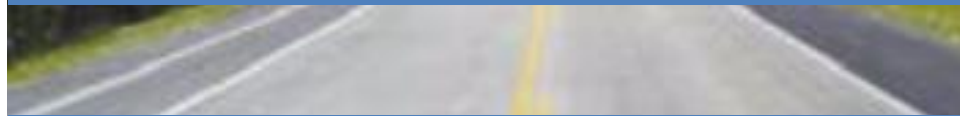
Treatment	Composition
Slurry seal	6.5 kg crushed fine aggregate and 0.68 kg residual asphalt per m ² pavement
Styrene acrylate reflective coating	7.7% styrene, 6% titanium dioxide, 13% butyl acrylate, 5.4% methyl acrylate, 3% methacrylic acid, 6% zinc oxide, 0.18% ammonium persulfate, 0.1% N-dodecyl mercaptan, 0.02% ammonium sulfite, 1.6% hydroxypropane-1-sulphonate, 1% aziridine, 1% ammonium hydroxide, and 55% water by mass, applied at 1 kg per m ² pavement

We evaluated 3 pavement scenarios: routine maintenance, rehabilitation, and long-life rehabilitation (ii)

Mill-and-fill asphalt concrete (AC)



Bonded cement concrete overlay over asphalt (BCOA)



With no, low or high supplementary cementitious materials (SCM)

Rehabilitation case study

Treatment	Composition
Mill-and-fill AC	38% coarse aggregate, 57% fine aggregate, 5% dust, 4% asphalt binder, and 15% reclaimed asphalt pavement by mass
BCOA (no SCM)	1071 kg coarse aggregate, 598 kg fine aggregate, 448 kg cement, 1.8 kg polypropylene fibers, 1.9 kg water reducer (Daracern 65 at 390 mL per 100 kg of cement), 1.6 kg retarder (Daratard 17 at 325 mL per 100 kg of cement), 0.6 kg air entraining admixture (Daravair 1400 at 120 mL per 100 kg of cement), and 161 kg water per m ³ wet concrete
BCOA (low SCM)	1085 kg coarse aggregate, 764 kg fine aggregate, 267 kg cement, 71 kg fly ash, 1.8 kg polypropylene fibers, and 145 kg water per m ³ wet concrete
BCOA (high SCM)	1038 kg coarse aggregate, 817 kg fine aggregate, 139 kg cement, 56 kg slag, 84 kg of fly ash, and 173 kg water per m ³ wet concrete

Case study	Typical treatment	Less-typical treatment	Aged albedo	Albedo increase	Service life (y)	Thickness per installation (cm)	Thickness installed over 50 y (cm)
3. Long-life rehabilitation	Mill-and-fill AC		0.10	-	20	15	37.5
		3A: BCOA (no SCM)	0.25	0.15	30	15	25
		3B: BCOA (low SCM)	0.25	0.15	30	15	25
		3C: BCOA (high SCM)	0.25	0.15	30	15	25